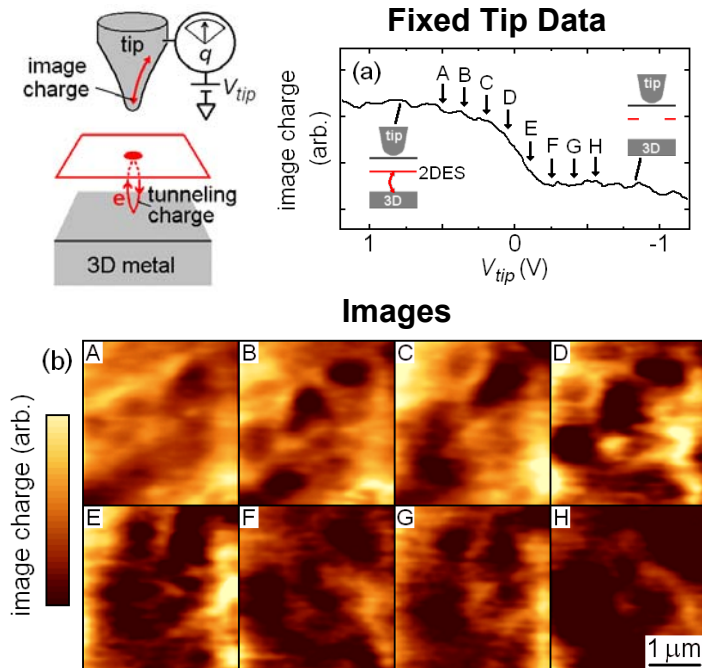


Charge Imaging Electrons in Nanoscale Systems

Stuart Tessmer, Michigan State University, DMR-0305461

Realizing the full potential of nanoelectronic devices requires a fundamental understanding of the behavior of electrons at the nanometer scale. We apply a novel scanning technique, Charge Imaging, to resolve directly the quantum structure of electrons in these systems. Here we present data for two-dimensional electrons trapped in a GaAs heterostructure. As shown in the schematic, electrons enter by tunneling from an underlying electrode, which induces image charge on a sharp metal tip. This signal is detected using a low-temperature transistor with a sensitivity of $0.01 \text{ electrons}/\sqrt{\text{Hz}}$. The data show surprising spatial structure for the electron density – suggesting that unexplained micron-scale disorder dominates the system.

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We apply Charge Imaging to detect electrons entering a two-dimensional electron system, outlined in red in the schematic. (a) Fixed-tip data showing a steplike reduction in the image charge as a depleting voltage is applied to the tip. (b) Corresponding images showing that the electron density variations tend to form micron scale droplets. The data were acquired at a temperature of 1.5 K.

We develop and apply low-temperature scanning probe techniques to study electrons in nanoscale systems. The techniques include Charge Imaging -- a novel low-temperature probe of electron accumulation. The techniques rely on a sharp needle (a.k.a. tip) which is positioned very close to the surface of a sample and then scanned sideways. All scanning probe techniques monitor some interaction between the tip and the sample to create an image. In the case of Charge Imaging, the quantity we monitor is the electric charge which appears on the tip in response to charge motion within the sample. This charge on the tip is called image charge. In the experiment presented here, the tunneling charge which enters the two-dimensional system determines the amount of image charge on the tip. In this way, we can measure how easily the two-dimensional system can accommodate additional electrons. The method achieves an incredible sensitivity of 0.01 *electrons per root hertz*. This means that under suitable conditions, we can resolve individual electrons entering the system. We believe our measurements will contribute to the further development of gallium-arsenide-based nanoscale devices, including the potential to use this system for applications relating to quantum computing.

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Education:

This project has provided an education in advanced surface science and scanning microscopy techniques to seven undergraduates, four graduate students, and one postdoc. These students have contributed either to the development or to the application of our novel scanning probe methods.

Outreach:

We are currently developing an educational scanning probe microscopy demonstration to be showcased in the Michigan State University Science Theatre, a project funded by this grant. The demonstration will be performed for students in grades 6-12 and will literally be a hands-on introduction to the

world of nanoscience. Undergraduate student Katie Thomas has made considerable progress designing and assembling the apparatus, as part of the NSF Research Experiences for Undergraduates (REU) program.



Katie presents the instructive components of the demonstration to fellow REU students. The inset shows the first iteration of the scanning assembly.